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AND TITAN**

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Abstract

The Cassini/Huygens mission is a joint endeavor between NASA, the European Space Agency, and the Italian Space Agency to send a spacecraft to perform an extensive exploration of the Saturnian system, including an atmospheric probe to go to the surface of Titan. The spacecraft was launched on October 15, 1997, and now has completed five years of its nearly seven year journey to Saturn. The cruise period has been a relatively passive time for the spacecraft, but an intensely busy one for the flight team. There is now less than two years to go until arrival at Saturn, and a significant portion of the effort deliberately planned for the post-launch period remains to be completed. Ground activities include the development of flight software, ground software, and science observation plans in order to be prepared to operate the mission after arrival at Saturn. This paper provides an update to the mission status and progress over the past year.

Introduction

The Cassini/Huygens mission is a joint endeavor by NASA, the European Space Agency, and the Italian Space Agency to conduct an extensive exploration of the Saturnian system. Detailed investigations will be made of Saturn's atmosphere, its rings, its magnetosphere, Titan, and the smaller icy satellites. The spacecraft, launched October 15, 1997, is comprised of a Saturn orbiting craft carrying 12 scientific instruments, and an atmospheric probe carrying six instruments. The probe will be carried into Saturn orbit with the orbiter and subsequently released, targeted for the atmosphere of Titan. As of the 53rd IAF Congress, the spacecraft has completed five of its almost seven year trip

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from launch to Saturn, and is about midway in time between its Jupiter flyby in December, 2000, and its encounter with Saturn on July 1, 2004. The performance of all spacecraft systems continues to be excellent.

Figure 1 shows the path of Cassini from launch to its arrival at Saturn, including its two extra initial orbits around the sun and four planetary flybys which were designed into the trajectory in order to gain the required energy to reach Saturn. The positions of Cassini today as well as one year ago are shown.

Activities on the spacecraft continue to be minimal during the interplanetary cruise phase, consisting primarily of instrument calibration activities and spacecraft and instrument maintenance. Navigation orbit solutions are done quarterly and trajectory correction maneuvers are done approximately annually, driven more by the need to do maintenance of the propulsion subsystem than control of the trajectory. The principal activities of the team over the past year have been the planning and design of the science sequences to be flown in the tour, development and testing of the final flight software loads to go to the spacecraft next spring, development and testing of the special sequences that will run on the spacecraft for the orbit insertion burn and the probe data relay, and final development of the ground software and procedures needed to conduct tour operations.

Navigation

The spacecraft has been approximately on track for the Phoebe encounter on June 11, 2004 since the Jupiter flyby in December, 2000, but annual flushing of the propellant lines is performed to prevent condensates from forming in the propellant in the lines and causing obstructions in the line filters. The

CASSINI MISSION CRUISE TRAJECTORY
Earth (E), Jupiter (J), Saturn (S), and Cassini (C) locations on 16 October 2002

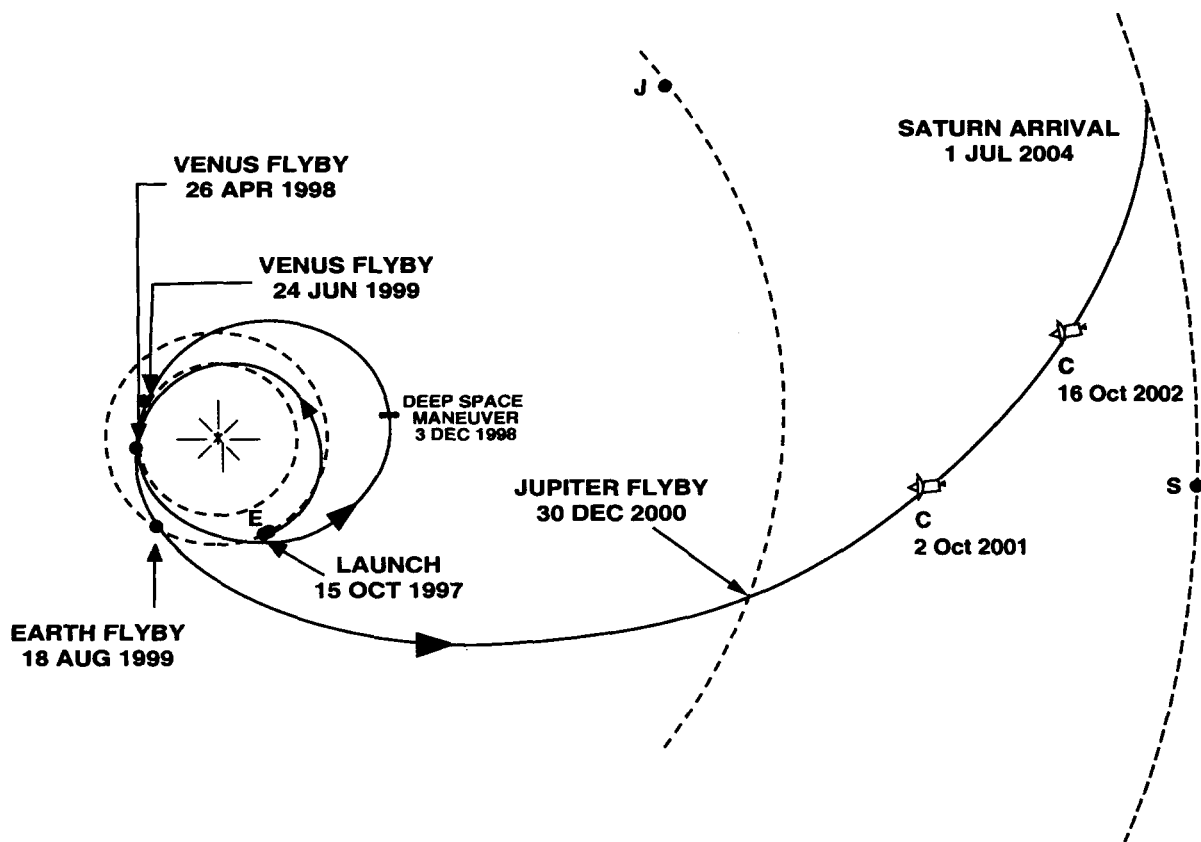


Figure 1 *Cassini Mission Cruise Trajectory*

effect of these relatively small ΔV s, around 0.5 m/s, must be accounted for in the design of the trajectory. Figure 2 shows the planned Saturn B-plane target points for the last four TCMs leading to Saturn encounter and SOI. The first of these, TCM-18, was performed on April 3, 2002. The target for this maneuver is shown by an X, the current solution point for the result is indicated by the +, and the 1-sigma solution uncertainty is represented by the ellipse. The next maneuver, TCM-19, is scheduled for May 1, 2003. The trajectory change needed to accommodate the 0.5 m/s necessary to flush the propellant lines is mostly in arrival time at Saturn, which doesn't show in the figure. The placement of these target points close to the Saturn impact circle is a coincidence of the trajectory design required to place Cassini on a trajectory passing 2000 km from Phoebe. TCM-20 is a deterministic maneuver of about 35 m/s occurring ten days prior to Phoebe closest approach which will be mostly a dog-leg type maneuver to reach the proper point for the ring plane crossing prior to SOI. TCM-21 also has a small deterministic component,

but primarily is intended as a clean-up maneuver of the normally occurring dispersions associated with a maneuver the size of TCM-20. A window has been established for TCM-22 at SOI - 10 days, but this is strictly for contingency planning. The delivery accuracy capability of TCM-21, when compared with the accuracy requirements at the ring-plane crossing point, indicate that there is no expectation of needing this maneuver. Nevertheless, the team will be fully prepared to perform it should it prove to be required.

Science Planning

Planning for the science observations to be made during the Saturn orbital tour has been a major effort for the Cassini Team over the past year, and will continue to be for at least the next two years. The magnitude of this task is driven by a number of factors, principal among these being the large number of instruments (12) to be making observations and the spacecraft design where the instruments are

mounted directly to the spacecraft bus. These features lead to many conflicting observation requests which must be negotiated and resolved in the course of building observation sequences. The intensity of operations during the four year Saturn tour is going to be such that it is essential that a substantial portion of the sequence design be completed prior to arrival at Saturn.

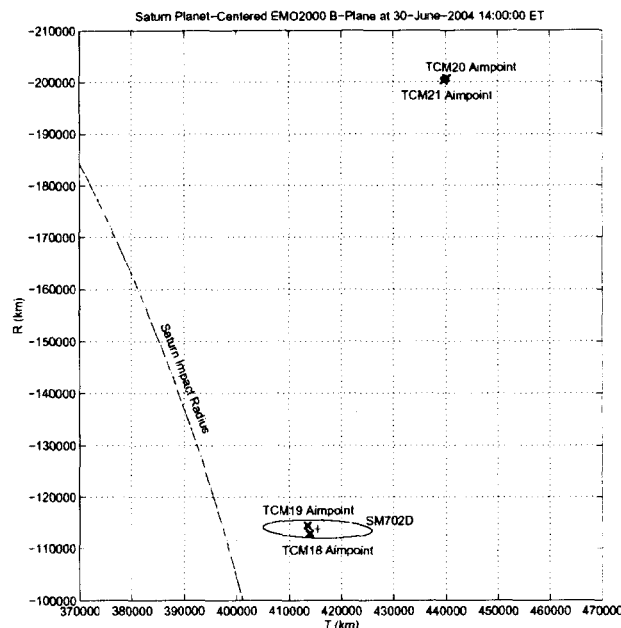


Figure 2 Saturn B-Plane Target Points

The pre-arrival portion of the science observation planning is made up of three components: observation identification, integration, and implementation. In the observation identification phase, all investigators identify all observations they would like to make to perform their investigation. Since this process results in a heavily oversubscribed set of activities, the requests are prioritized into must-have, important-to-do, and would-be-nice-to-have to aid the subsequent negotiations. This part of the science planning task is complete. The integration component is where the negotiations take place to arrive at a timeline of observations that are mutually conflict free among the different instruments. This process necessitates looking over the entire four years of the tour to determine where various measurement objectives can be achieved. In deciding between two or more mutually exclusive activities at a given time, it is important to understand which of these might

be achieved at a later time, versus the current opportunity being the only one in the entire mission. This activity was begun in August, 2001, and will complete in January, 2004. The implementation phase is where the integrated timeline of observations is developed into a sequence to the level of detail of defining the pointing profiles necessary to implement the observations, and the strategy for handling the acquired data. The design of the pointing profiles is a more involved task than it might appear to be due to the requirement to turn the entire spacecraft to point the instruments. Along with this comes a number of pointing constraints related to the safety of the spacecraft and instruments. Examples of such constraints include attitudes which point instrument boresights to the sun, which bring bright light sources into the field-of-view of the star trackers, which illuminate, and hence heat up various instruments' radiators, etc. Factoring in turn time restrictions for what can be approaching 100 turns per day further complicates the task. The Cassini spacecraft attitude is controlled by either small thrusters using hydrazine or by reaction control wheels. The wheels are the preferred mode of control because they provide greater pointing accuracy and stability and don't use any consumable such as the hydrazine used by the thrusters. However, they have less control authority than the thrusters, and hence take longer to reach a specified attitude, which can be a significant issue when making observations on a tight timeline such as at a satellite encounter.

The second major aspect of the implementation part of science planning is that of the data handling strategy. Another consequence of having the instruments body fixed is that data cannot be returned to Earth during periods of data acquisition and conversely only very limited data taking can be accomplished during periods that the high-gain antenna is pointed to Earth. The general plan for data acquisition and return is to use 16 hours of each day for acquisition followed by 8 hours of Earth pointed playback, with variations as needed to accommodate high priority data collection opportunities. Data acquired during the data collection phase is stored on the two solid state recorders (SSR) with a combined data capacity of almost 4 gigabits. Data return capability is limited by either the SSR capacity, or by the DSN downlink data rate capability. The latter capability is influenced by the length of the pass, whether 34m or 70m

stations are used, whether or not station arraying is used, and whether Cassini is near a period of opposition or conjunction with Earth. The communication range varies between approximately 8 and 10 AU between opposition and conjunction, respectively. Development of a data management strategy involves determining when DSN tracking passes will be scheduled, how much data is to be stored, whether or not data will be carried over from before one pass to a later pass, etc. Science planning implementation is complete for a given sequence when a viable, violation-free pointing profile has been developed, and an associated data management plan has been identified. Implementation started in May, 2002, and will be complete in early 2005. This is after the spacecraft is in orbit about Saturn, and is later than is desired, but the scope of the task made an earlier completion date impractical.

Flight Software

One of the major decisions made when structuring the Cassini Project was to deliberately plan a substantial part of the development effort for after launch. One side-effect of this was that it gave the project the appearance of having a large staff to maintain a spacecraft that was doing relatively little. However, there were two very substantial benefits to be gained by this plan. One is that it provided a mechanism for having a well trained and experienced staff in place and ready to operate both the spacecraft and ground system once the primary part of the mission at Saturn began. The second benefit is that it allowed the team to modify its procedures and software capabilities and design based on actual in-flight experience in operating the spacecraft, both for flight and ground software.

The two principal onboard processors are the Attitude and Articulation Control Subsystem (AACS) and the Command and Data Subsystem. Each of these subsystems is a fully reprogrammable processor. Both had adequate code at launch to support launch, initial navigation, and flight hardware and science instrument maintenance, but both also had considerable capabilities remaining to be implemented before such functions as reaction wheel control, orbit insertion, probe relay, and tour operations could be performed. The first in-flight load of new software for both subsystems was done in May of 2000. These

loads provided significant new capabilities that were then used a few months later during the Jupiter flyby in December, 2000. The availability of these capabilities was a key factor in making the Jupiter flyby be a reasonable dry-run of operations in the tour, and led to significant changes in ground processes and software that will be used at Saturn. Since this time, additional flight software capabilities have been in development and testing, primarily aimed at supporting the sequences that will be run to perform SOI and the Huygens probe data relay, but also some additional capabilities for tour. This last set of code is currently in hard freeze, is undergoing intensive testing, and is scheduled for uplink to the spacecraft in February and March of 2003. This schedule is designed to give ample burn-in time in flight prior to the critical events coming in a little over one year.

Critical Sequences

A significant level of effort has gone into developing and testing the sequences that will execute on the spacecraft to perform SOI and the probe data relay. These two sequences are unique compared to all other sequences that will run on the spacecraft (except launch) in the sense that their execution to completion at a single fixed time is essential to mission success. All other sequences could be aborted and either simply not ever be done or done at a later time. Such an event other than at SOI or probe relay would have some impact on the mission, ranging from some rework later to loss of some data or perhaps added propellant usage, but in any event would not be considered mission catastrophic.

For SOI, there is some very limited flexibility in when the orbit capture burn can be accomplished. For minimum propellant usage, the burn, which is about 1.5 hours in duration, would be approximately centered on Saturn periapsis. However, for the Cassini mission, the burn has been shifted to start about 30 minutes earlier than the optimal time to gain two benefits, one for science and one to increase the likelihood of a successful orbit insertion. The science gain comes from the fact that the orbital geometry near the initial Saturn periapsis brings the spacecraft through the ring plane at a distance of 1.6 Rs altitude above Saturn's surface, over the rings and in to a closest approach of 1.3Rs at about

25,000 km above the rings, and then back to descend through the ring plane again about three hours after the initial crossing. By placing the burn early in this three hour period at a ΔV cost of about 28 m/sec, about 75 minutes can be given to science to make observations of the rings with unique lighting conditions and at a range considerable less than will be available at any time again in the mission. The increased reliability comes from the fact that the Cassini spacecraft has two main engines, one prime and one spare, and software logic to permit the spacecraft to respond autonomously to various faults. If some anomalous condition prevents engine ignition at the prescribed time, this logic can, in some circumstances attempt a later ignition. If one engine fails during the course of the burn, this logic can swap engines and after some cool-down delay, start the second engine and continue the burn. Although such events are considered highly unlikely, by starting the nominal burn earlier than might be otherwise desired, the ability to respond to such faults and still complete a successful orbit insertion is enhanced by the earlier maneuver placement. Since this approach leads to the possibility of varying locations in the orbit where the ΔV may be applied, there is no longer a unique ΔV magnitude that yields the desired post-burn orbital energy, because the change in energy per unit of ΔV is a function of true anomaly. To accommodate this, an algorithm has been developed to run on-board the spacecraft that calculates the achieved orbital energy based on knowledge of orbital position and the ΔV versus time profile from the accelerometer to determine when to command burn termination.

generally puts the spacecraft in a safe state to await further instructions from the ground. Obviously such a response can not be accepted during SOI or probe data relay, since these are both events that can only occur at a very specific time, so these two sequences are executed in what is called critical mode. In this mode, some fault protection responses are disabled, but not all. Safing during a time when the spacecraft is not in critical mode will leave the spacecraft either Earth-pointed or sun-pointed, depending on the nature of the event that caused safing to occur. However, any safing during either SOI or probe relay must maintain the proper attitude in order to allow the event to run to completion.

NAC Contamination

Periodic instrument maintenance is performed on most of the Cassini instruments to insure their continued health over the course of the long cruise from launch to the approach to Saturn and the beginning of regular, active use of the instruments. Specifically, the detectors for both the Narrow Angle Camera (NAC) and the Wide Angle Camera (WAC) were heated to 30°C about every 3 months to avoid any accumulation of contamination. Star images taken from time to time verified the absence of any such problem. The normal detector operating temperatures are around -90°C. However, during the Jupiter encounter in late '00 and early '01, when the cameras were in regular use collecting Jupiter images, they went for a little over a year without being heated, which is the same operating strategy



Figure 3 NAC Anomaly Resolution Timeline

The spacecraft software contains fault protection logic which is designed to protect the spacecraft in the event of some anomaly. For certain types of anomalies, the software will run safing code which halts the currently running sequence, turns off all non-essential power loads, such as science instruments, and

planned for operations in the tour. In May, '01, after a routine decontamination heating was completed, subsequent images of Saturn showed a substantial haze in the images. An investigation followed to determine the source of the contamination, and what would be the most prudent response to it. Starting in

October, 2001, a series of detector warmings was implemented at temperatures initially at -7°C , and eventually up to $+4^{\circ}\text{C}$. These warming cycles were repeated from October, 2001 through to mid-June, 2002 with durations from one week to two months in length, and with observations taken between cycles to assess the response of the detectors.

Figure 3 shows a chronology of this effort. The image on the left is of the star SAO 88160 taken in May, 2001, and is the last observation made before the decontamination cycle that appears to have led to the detector contamination. The second image is of the star Maia taken on May 30th, and is the second image taken after the problem occurred. The image in the center is of Spica, taken on October 26, 2001, after the first decontamination cycle of seven days at -7°C . The response of the detector was encouraging, at least it showed an improvement in response to the heating, but was far from correcting the problem. The next to last image (second from right) is again of Spica, and was taken in January, 2002 after another seven days of heating, this time to $+4^{\circ}\text{C}$. Between January and July, 2002, three more warming cycles were completed for a total duration of 116 days at $+4^{\circ}\text{C}$. The image on the far right, again of Spica, was taken in July and shows an image quality comparable to that before the contamination first appeared.

The source and the mechanism of the contamination are still not understood. The only difference in the camera maintenance practices since launch was the long period around Jupiter without a decon cycle. Knowledge of how such contamination can be removed is encouraging, but obviously such a series of warming cycles in the tour would be highly disruptive to imaging science data collection, since image taking requires a cold detector. At the moment, no additional detector warmings are planned, but the issue is still under investigation.

Summary

Things are going very well for the Cassini/Huygens mission. The spacecraft is performing essentially perfectly. The ground activities needed to be ready for arrival at Saturn in about a year and a half are progressing on schedule. Much remains to be done, but the team is experienced, dedicated, and functioning well. The next major event is Saturn orbit insertion on July 1, 2004.

Acknowledgments

The work described in this paper represents the work of the entire Cassini team, including the current flight team at JPL, a large group of scientists from across the United States and Europe, as well as the engineers and supporting staff who designed, built, and launched this marvelous spacecraft.

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